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Simulation of Particle Spectra at RHIC*

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A purely hadronic simulation is performed of the recently reported data from PHOBOS at energies of $\sqrt{s} = 56, 130$ GeV using the relativistic heavy ion cascade LUCIFER which had previously given a good description of the NA49 inclusive spectra at $\sqrt{s} = 17.2$ GeV/A. The results compare well with these early measurements at RHIC and indeed successfully predict the increase in multiplicity now seen by PHOBOS and the other RHIC detectors at the nominal maximum energy of $\sqrt{s} = 200$ GeV/A, suggesting that evidence for quark-gluon matter remains elusive.

25.75, 24.10.Lx, 25.70.Pq

I. INTRODUCTION

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory was constructed with the explicit purpose of creating and analysing a form of hadronic matter referred to as quark-gluon plasma. Certainly partons, when struck with sufficient energy, may acquire enough momentum to travel beyond the confines of their host hadron. In $p+p$ experiments at the RHIC energy of $\sqrt{s} \sim 200$ GeV/c the contribution of such 'jets' to the inclusive production of π mesons is not large, perhaps less than 5% [1]. Nevetheless, sufficient thermal energy can possibly be pumped into a massive ion-ion system, via production of the less well defined "mini-jets" [1], to free or create large numbers of partons in an ion-ion collision. The existence and precise nature of any ensuing phase change, from infinite hadronic to partonic matter [2], is still the subject of debate. Truly macroscopic systems in which plasma might be realised do exist in nature, in the early universe or in a neutron star [3]. Although for a finite system the question whether an actual phase change occurs may be somewhat academic, one might still hope to identify a deconfined mode by sufficiently sharp, rather than truly discontinous changes, in appropriate observables. For example, the transverse energy measured in an ion-ion collision can be used to define, in a model, the system temperature and the relationship to say the density, of the number of mid-rapidity pions as established by experiment. The hadron number density is a measure of the entropy created in the collision, a quantity definable even for a non-equilibrium finite system, and one reasonably expected to be highly sensitive to the increase in degrees of freedom accompanying parton deconfinement.

Here, we address only the most recent and remarkably prompt measurements by the PHOBOS [4,5] collaboration at RHIC. The highly successful, early running of the RHIC facility, albeit at lower than the ultimate energy and luminosity, together with this efficient small detector have already provided the heavy ion community with interesting, perhaps even provocative results. We analyse the PHOBOS results theoretically with the hadronic cascade LUCIFER [6,7], adopting the position that this analysis simply presents an extrapolation from the earlier NA49 inclusive measurements [11] to the considerably higher energy RHIC determinations. The other detectors at RHIC have confirmed these early PHOBOS results, certainly at $\sqrt{s} = 130$ GeV [8–10] and by now even at $\sqrt{s} = 200$ GeV (see Proceedings of this workshop).

It seems appropriate to compare these initial observations at RHIC with simulations which assume no plasma is present. The purest such comparison would employ a model involving only hadronic degrees of freedom. A recent comparison does exist with the partonic code HIJING [12]. The instrument for the present exploration of the RHIC domain is the code LUCIFER, described in detail elsewhere [7] and available by downloading from a BNL theory home page. Suffice it to say that this simulation was prepared for use at relativistic energies attainable at RHIC and tested against the CERN SPS heavy-ion experiments. This purely hadronic simulation gave a good account of the two general particle production experiments at the SPS, those for S+U and for Pb+Pb [7,11,13]. Thus LUCIFER might be used as a standard against which to place the very interesting results from PHOBOS; a means for defining the 'ordinary'

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in proceeding from the SPS to RHIC. This can be accomplished by a slight tuning of LUCIFER multiplicities to provide very close to quantitative agreement for the SPS π^- rapidity spectrum. In retrospect [6], the predictions for the latter spectrum were perhaps $10 - 15\%$ high when compared with the latest NA49 h^- determination [14].

One possibility, exploited in our methodology, is that to some extent an ion-ion collision is describable by multiple interactions between excited hadrons only. In such a picture the constituent quarks are excited to states differing from those present in the lowest mass baryons or mesons, but the glue holding them in place is still 'sticky'. The quarks continue to act as if still confined within some hadron. This description was feasible in say the Pb+Pb collisions examined in NA49 [11]. It remains to be seen whether at the higher RHIC energies a large fraction of these quarks are free to roam over large spatial distances, and more importantly perhaps whether sufficient 'free' gluons are present to create the thermodynamic basis for hadronic material describable as quark-gluon plasma.

Many simulations and/or cascades [7,12,15–21] have been constructed for relativistic heavy ion collisions. Some of these are purely partonic cascades, some are hybrids of hadronic and partonic cascading. LUCIFER [7] is a two stage hadronic cascade run sequentially through two stages. In the initial rapid phase I, at high energy, no energy loss is permitted for soft processes; however the complete collision histories are recorded. The time duration of phase I, t_{AB}, is that which would be taken by the two colliding nuclei to pass freely through each other. Hard or partonic processes for which $p_t \geq t_{AB}^{-1}$ could be introduced in this mode and consequent energy loss allowed for.

The second stage, phase II, is a conventional hadronic cascade at greatly reduced energy, similar to that applicable at the AGS and for which soft energy loss is allowed and chronicled. This second cascade begins only after a meson formation time, τ_f, has passed. Using the entire space-time and energy-momentum history of phase I, a reinitialisation is performed using an elementary hadron-hadron model, fixed by data [7,22,23] as a strict guide. Nucleons travel almost along the light-cone in phase I, but the number and types of collisions they suffer are instrumental in generating the produced mesons which will participate in phase II. Participants in the second phase are treated as generic mesons, thought of as of $q\bar{q}$ states with masses centered near 700 MeV and in the range $0.3 - 1.0$ GeV, and generic baryons consisting of qqq excited states also with rather light masses, $0.94 - 2.0$ GeV [7]. This same specrum of hadrons is of course used to describe the known elementary baryon-baryon and meson-baryon collisions and the parameters of the model are thereby determined. In the end, the cascade is exploited to derive predictions at the higher energy solely from knowledge of two body interactions and from a general structure which worked well at the lower $\sqrt{s} \sim 20$ GeV SPS level.

In phase II of the ion-ion interaction, the generic resonances decay into stable mesons and baryons as well as colliding with each other. The low mass of the generic hadrons guarantees that the transverse momentum acquired in any chain of interactions or decays will be relatively small, and hence one is modeling only soft processes. A deeper analysis might add parton production in phase I and cascading perturbatively. Also, and crucially, the sequential decay of the interacting generic hadrons into several mesons and baryons severely restricts the particle multiplicities and thus the amount of cascading during early stages of phase II. We had previously included in our modeling [7] a suggestion by Gottfried [24] that the secondary particles produced in elementary two-body collisions within nuclear matter should not be considered to exist for the purpose of secondary interactions until they had sufficiently separated themselves from each other. Implementing such a constraint effectively limits the density of interacting generic hadrons in stage II to non-overlapping configurations. A very simple but accurate representation of this procedure results from just constraining the multiplicity at the end of phase I by this criterion, and in practice the calibration at the NA49 energy $\sqrt{s} = 17.2$ GeV then sets the constraint at all energies.

We refer readers to the above mentioned references for more details of the simulation, the major physical assumptions and measured elementary hadron-hadron inputs. The most important inputs from elementary cross-sections involve the total nucleon-nucleon and meson-nucleon cross-sections and of course the division into elastic, single diffractive(SD) and non-diffractive production(NSD). The multi-prong UA(5) [22] data leading to multiplicity distributions for meson productions in the latter two categories are crucial.

A concomitant problem in the search for quark-gluon 'plasma' is to distinguish between such a state and simple medium dependence in a hadronic gas. We constrain the hadronic cascade by imposing no explicit collective effect of the internuclear environment: however, one could still possibly ascribe any departure between cascade predictions and measurements to the A dependences of both particle properties and interparticle forces on the conditions obtaining during the nuclear collision. For example, the apparently anomalous dilepton spectrum at the SPS [25] is frequently attributed to medium dependent shifts in the masses of certain vector meson resonances. We have proceeded without introducing any medium dependence.

At RHIC energies the time duration of phase I, $t_{AB} \sim d_{AB}/\gamma_{-1} \sim d_{AB}/200$ with d_{AB} being the combined size of the colliding nuclei, is an order of magnitude shorter than at the SPS. Moreover, phase II of the cascade at RHIC energies is a more serious matter. It occurs at higher energies, creates relatively more mesons and lasts for a longer time. At the SPS [7] we determined the meson formation time, τ_f, from collisions of light ion systems, e.g $S + S$, and we employed this same time, τ_f, in the massive Pb+Pb system. Inherent in this procedure is the assumed insensitivity of τ_f to mass number, collision energy, etc, suggests that we must use the same τ_f at RHIC energies, i. e. $\tau_f \sim 1.0$

fm/c. It would be preferable to recalibrate this parameter, essentially the only one in our modeling not determined from two body data, with similar measurements on the light nuclear systems at RHIC. The totality of mesons, particle and energy densities produced in the cascade are to an appreciable extent controlled by τ_f, for obvious reasons. For the moment and to avoid the introduction of any other parameters, we employ the same τ_f at all energies.

To facilitate comparison with the computations at $\sqrt{s} = 56, 200$ GeV, we present here LUCIFER results [7] for Pb+Pb at $E_{Lab} = 158$ GeV. These appear in Figure 1 and are there compared to recent NA49 data [14]. As we described above the code was re-adjusted in this figure to give near the latest NA49 $dN/dy(y = 0)$ for negatively charged hadrons, π^-'s for the most part.

In earlier work [7], we studied the relativistic invariance of the model, and demonstrated that for a worst case scenario, i. e. a zero impact parameter Au+Au collision at 200 GeV, frame dependence in the cascade, produced by the action at a distance assumptions inherent in the theory, and as measured by the variation in $(dN/dy)_{\pi^-}(y = 0)$, was $\leq 10\%$, and virtually nonexistent at SPS energies. Calculations in the present work are performed in the equal velocity frame for which the errors are undoubtedly less.

We now exhibit typical meson production expected at RHIC in a purely hadronic simulation. Configurations of the greatest interest involve the most massive ions in the most central collisions. It is here that one might hope to see greatest measured deviations from our simplified purely hadronic, medium independent picture. For simplicity, we specify centrality here by geometry and initially select $b \leq 4$ fm so as to approximately reproduce the 6% cut specified by PHOBOS [4]. Variations in production levels with impact parameter are not too severe but some error attaches to the precise definition of centrality. We present results both for the for the two energies $\sqrt{s} = 56 and 130$ GeV reported by the PHOBOS collaboration [4], as well as for the higher RHIC design energy of $\sqrt{s} = 200$ GeV. The latter constituted a prediction.

The simulation results obtained at SPS energies derived mainly from the above mentioned inputs: the two body energetics and the totality of nucleon-nucleon interactions in the course of an event. Although the time for phase I is considerably compressed at the higher RHIC energy, we expect much the same characteristics determine production levels as at the SPS. A somewhat increased importance for the second, conventional, cascade in Au+Au at RHIC is observed.

The results of the LUCIFER simulations for $\sqrt{s} = 56, 130$ GeV are displayed in Figure 2, where they are compared to the corresponding PHOBOS measurements [4]. The minimum conclusion to be drawn from the cumulative evidence of 1 and 2 is surely that LUCIFER provides a satisfactory explanation of the PHOBOS mid-rapidity charged meson density determinations, consistent with the previous normalisation of the code to NA49 data. Additional information contained in Figure 2 is the predicted energy dependence for the later full energy runs as well as the shape of $\frac{dN}{d\eta}$ for the complete pseudo-rapidity range. Again, this prediction is apparently consistent with the latest PHOBOS measurements [4].

One interesting aspect of the LUCIFER simulation relates to the numbers of final, observed, mesons with and without the inclusion of phase II. With the second stage rescattering turned off, all of the final hadrons are produced from decays of generic resonances generated in phase I. It is on the generic hadrons present after phase I that an effective multiplicity constraint is placed by normalizing to the SPS data. This initial multiplicity directly determines the important early particle and transverse energy densities. Phase II begins only after a pause, dependent on τ_f and the relativistic factors γ for the secondary mesons. Thus, particles produced in phase II begin to materialise only when the interaction region has increased considerably in size. The combined multiplicity increase from phases I+II over phase I plus decays alone is about a factor 2.25 at $\sqrt{s} = 130$ GeV. This reasoning suggests that it is dangerous to tie the final measured $dN/d\eta$, in say PHOBOS, to an initially achieved E_T density and to the inference of plasma formation. Thus the calculated increase in total particle multiplicity from the SPS to RHIC, ~ 2.5, is no indicator in our model that plasma formation at the higher energy has occurred or was more likely. Indeed $dN/d\eta$, which is probably a better indicator of central densities during collisions, increases by less than a factor of 1.4.

The relatively low value of meson density found by PHOBOS is in itself interpretable as a lack of unusual medium dependence. The increase in entropy expected from the sudden release of additional parton degres of freedom ought to show up as a sharp increase of central $dN/d\eta$ for mesons. Of course mitigating effects like shadowing must be accounted for, but the PHOBOS $dN/d\eta(\eta = 0)$ must still be considered not high enough to be indicative of plasma formation, at least in these 'average' 6% events.

We also find in preliminary simulation that the tranvserse momentum spectrum at $\sqrt{s} = 130$ GeV, including the apparent "deficit" seen between p_t of 3 and 4 GeV/c, is well described provided the known UA(1) $p\bar{p}$ data [27] for h^+ is fitted. To accomplish this one must include both the π^+, k^+ (dominant at low p_t) and the proton (dominant at high p_t) contributions.

One can now surmise that the anticipated QCD matter behaviour will at least be harder to detect, and must be sought in rarer events. Perhaps one must proceed to an order of magnitude higher centrality, e. g. $\leq 1\%$, or better still to searching for large multiplicity fluctuations, in order to unearth unusual behaviour.

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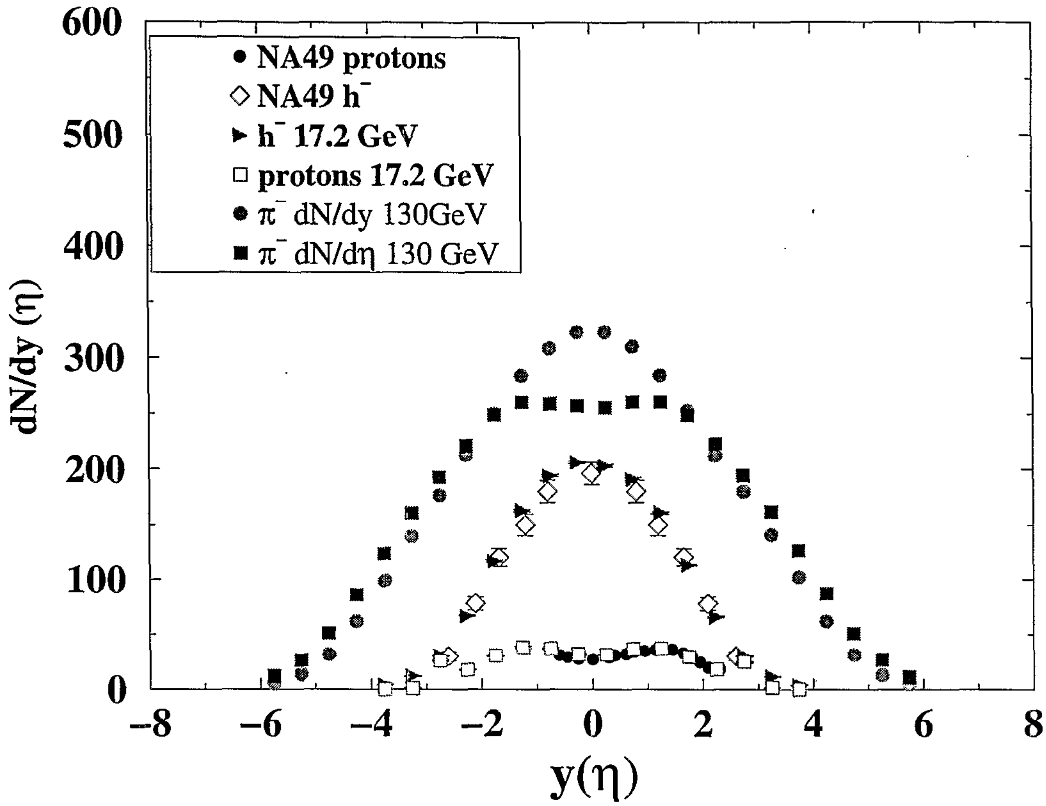

FIG. 1. Comparison between normalised LUCIFER and NA49 for h^- and protons from Pb+Pb at 158 GeV per nucleon (Lab). Also shown are rapidity and pseudorapidity distributions for π^- at $\sqrt{s} = 130$ GeV. The latter should be increased by $\sim 10-12\%$ to include k^- but are not corrected for the experimental low p_t cut.

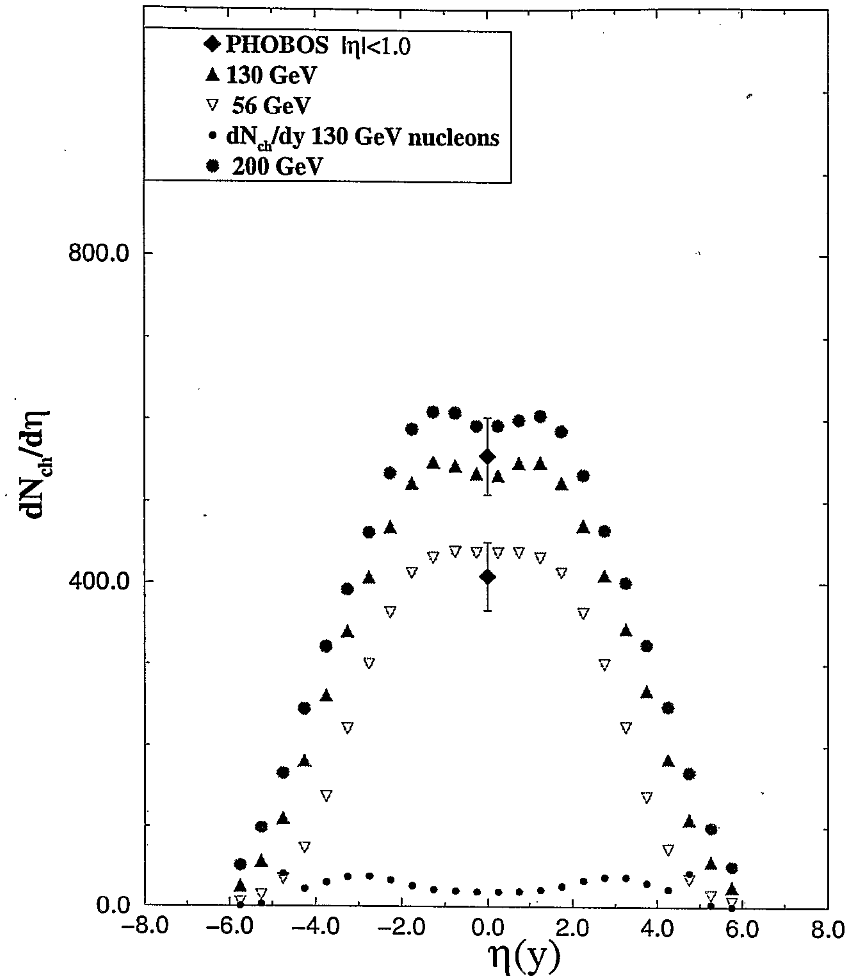

FIG. 2. Charged Mesons for Au+Au at RHIC energies of $\sqrt{s} = 56, 130$ GeV. Comparison with PHOBOS pseudorapidity averaged density measurements over the central two units of η. The LUCIFER spectrum for $\sqrt{s} = 200$ is also shown. Small renormalisations can be expected for all results from a centrality definition more consisten with individual experimental setups. The total mesonic production at $\sqrt{s} = 130$ GeV in these simulations is some 6600 particles compared to near 2500 at $\sqrt{s} = 17.2$ GeV. The nucleon spectrum in this figure is a funtion of rapidity y. The prediction for the full RHIC energy $\sqrt{s} = 200$, an increase of some 14%, is very close to the recent PHOBOS measurement.